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Computer simulation of high current vacuum arc with developed anode spot

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Abstract. A self-consistent simulation of anode heating by 4.5 kA vacuum arc during the half-wave of 50 Hz current with 1 m/s contact opening was carried out. The calculations were done in the framework of hybrid high current vacuum arc model, which treats ions and atoms as macroparticles with the help of particle-in-cell methods, but electron subsystem is treated as massless fluid with quasineutrality assumed. The occurrence of an anode plasma plume (similar to that found in experiments) was obtained as a result of modeling. It is shown that the energy flux of line radiation from the interelectrode plasma to the anode is a critical reason of the appearance and maintenance of the anode plume.

1. Introduction

High current vacuum arc (HCVA) is an arc with current in the order of several kiloamperes. Such kind of arcs is typical for vacuum interrupters or circuit breaker [1]. At the moderate current, the main source of plasma in HCVA is multiple cathode spots [2, 3]. However, when the current increases to a certain threshold value, the anode becomes an additional plasma source. The bright, well defined spot appears at the anode surface. This phenomenon is known as the anode spot [4, 5]. It was reported also that anode spot appearance sometimes accompanied by anode plasma plume in bright shell [6, 7, 8].

The appearance of the anode spot significantly reduces the ability of vacuum interrupters to switch off the current. Therefore, there is considerable interest in the study of this phenomenon from the industry of the production of interrupters. Despite the interest, the theoretical models for the emergence and development of the anode spot are relatively weakly developed. It would seem that, unlike the cathode spots, there should be nothing mysterious about the anode spots.

Schematically, the processes at the anode of the HCVA are as follows. At the beginning, due to the Hall effect, a constriction of the current near the anode occurs [9]. As a result, somewhere in the center of the anode, the density of the heat flux from the plasma to the anode increases significantly. Anode surface is heated up to a temperature at which the saturated vapor pressure becomes higher than the total pressure of near-anode plasma. After that, the anode vapor starts to flow into the interelectrode gap, where the vapor is ionized. Some difficulty in modeling this sequence is that for self-consistent determination of the anode surface temperature it is necessary to perform calculations along the half-wave of power frequency current. Since the characteristic times of plasma processes in the interelectrode gap are much less than a millisecond. Such calculations were carried out in [10] on the basis of MHD model [9]. It was shown that after the onset of intense evaporation of the anode, the



current-constricting mechanism gradually ceases to work. As a result, the initially small hot spot on the surface of the anode increases in size with increasing current, while the maximum temperature of the surface of the anode remains approximately constant. In the model [10], no mechanism was found that would ensure the existence of a well-defined overheated area on the anode that is necessary for the formation of an anode spot or plasma plume. Hall and pinch effects are too weak to provide this in the case of HCVA with evaporating anode.

In [5], there was an assumption about the existence of some Erosion-Ionization instability, which ensures the development of the anode spot, but nothing similar was found in model [10]. The anode plasma plume was modeled in [11, 12], but this was not a self-consistent simulation, since the anode temperature was set arbitrarily. Thus, up to now, a self-consistent simulation of the appearance of the anode plasma plume in HCVA has not been performed. In this article we attempted to fill this gap.

2. Model description, calculation results and discussion

The processes of plasma creation, plasma anode interaction, and anode evaporation were self-consistently modeled using a previously developed two-dimensional axisymmetric hybrid model [13, 14]. The hybrid model allows to direct simulate the evaporation (including Knudsen layer), ionization and charge exchange. In the hybrid model, ions and electrons are described using different approaches. Ions and neutrals are described with the help of particle-in-cell (PIC) approach, but electron subsystem is treated as massless fluid with quasineutrality assumed. Calculations were carried out for copper electrodes with a radius of 1 cm, a contact opening velocity of 1 m/s, and a half-wave current of 50 Hz with the current maximum of 4.5 kA (figure 1). These conditions roughly correspond to experimental configuration [7].

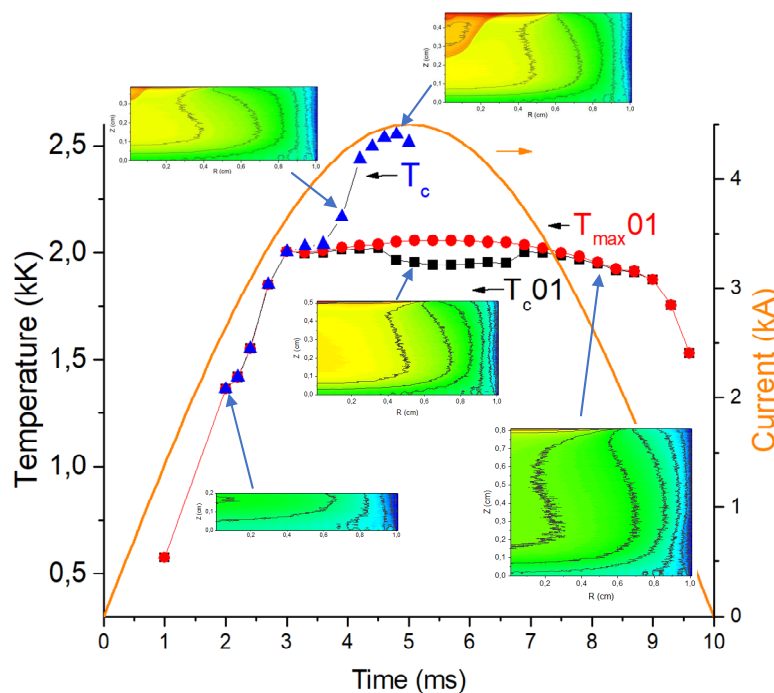


Figure 1. Evolution of anode temperature and arc appearance during half-wave of sinusoidal current. T_c – surface temperature in the anode center in case of fully absorbed falling radiation; T_{c01} , T_{max01} – surface temperature in the anode center and maximal anode surface temperature in case of partly (10%) absorbed of incident radiation. In the contour plots the logarithm of light radiation power after Abel transformation are shown (anode at the top).

Like in [10], the simulation along the half-wave of the current was carried out as follows. We found a stationary solution for plasma in the interelectrode gap for a specific current and the interelectrode gap size, taking into account the evaporation from the anode. Then the heat flux to the anode (like in figure 2) was calculated. Further, using the previous distribution of the anode temperature as the initial condition, we, by interpolating the heat flux to the anode, solved the non-stationary two-dimensional problem for the anode temperature development. After the anode surface temperature was updated, the solution for the plasma in the gap was recalculated. Thus, a series of stationary solutions for the plasma in the opening gap were found together with a non-stationary solution for the anode temperature development (figure 1).

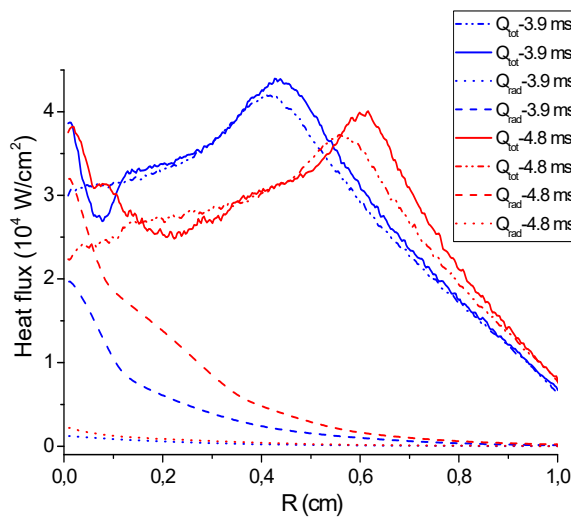


Figure 2. Radial distribution of heat flux density from plasma to anode for instants: 3.9 and 4.8 ms. Q_{tot} – total heat flux; Q_{rad} – radiation component of total heat flux.

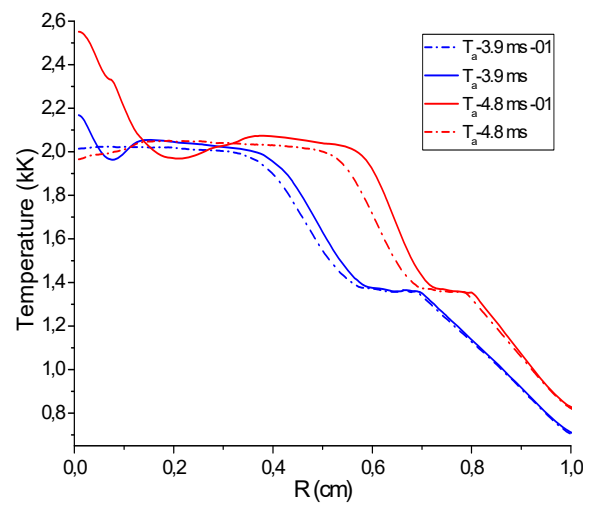


Figure 3. Anode surface temperature distribution for instants: 3.9 and 4.8 ms. Number – 01 marks the case with 10% absorption of incident radiation.

In model [10], only the electron, ion and atomic components of the heat flux to the anode were taken into account. The radiation flux from the plasma was not considered. In this model, the radiation flux from the plasma to the anode is additionally taken into account. This is the energy flux of line radiation from the plasma volume. Plasma is assumed to be optically thin. To estimate the effect of line radiation, we use a very rough (in this case) approximation – the approximation of truncated hydrogen atom [15]. Line radiation lost is calculated for each type of ions and for the atom.

The angular coefficients are used to determine the flux of light radiation energy to the anode [16].

These coefficients determine at what solid angle a given element of the anode surface is visible from the given element of the plasma volume. After integration over the plasma volume, the radiation energy flux into the anode is obtained. An open question is an emissivity factor (EF) of the anode surface. In the general case, EF depends on many parameters, including the frequency of the incident radiation, the state, composition and temperature of the surface, etc. In the paper, we consider solutions only for two values of the EF: 0.1 and 1. In the first case, the radiation almost does not affect the heating of the anode, in the second case, the radiation gives the maximum possible effect.

Comparison of the calculation results with two different values of EF is shown in figures 1–3. It is seen that in the case of $EF = 0.1$, the maximum temperature of the anode at $t \sim 3$ ms reaches a temperature of about 2 kK and remains approximately at the same level up to $t \sim 8$ ms (figure 1). The area of the hot spot on the anode increases (figure 3). And the density of heat flow to the anode decreases, even despite the increase in current (figure 2). This is due to the fact that after the onset of

strong evaporation from the anode, the injection of a cold, weakly ionized plasma into the gap leads to a general cooling of the plasma and weakening of the current constriction.

As a result, the maximum density of the heat flux to the anode decreases and shifts in the direction of the electrode edge (figure 2). In this case, the plasma-electrode heating system has negative feedback. As a result, local overheated areas do not appear on the anode surface. This result is consistent with the previous modeling [10].

After the start of evaporation, a cloud of weakly ionized plasma appears at the anode. The power of linear radiation increases dramatically. In the case of $EF = 1$, the resulting heat flow to the anode also increases sharply. Due to the geometry of the problem, the maximum light radiation energy flux is always in the center of the anode (figure 2). In this case, the system has positive feedback. Therefore, small overheated area appears in the anode center (figure 3). As shown in figure 1 and figure 3, the anode surface temperature in the center reaches approximately 2.6 kK. After overheating spot appeared a dense relatively cold plasma plume appears in front of the anode (figures 4–5). In our calculations the plasma plume appeared at $t \sim 4$ ms (figure 1), which is consistent with the experimental results [7]. Further, with increasing current, the size of the anode plasma plume increases.

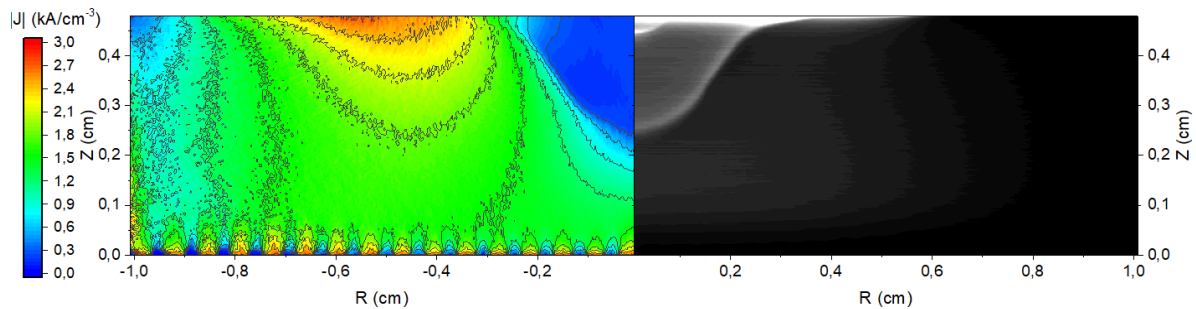


Figure 4. Left side – current density distribution, right side – reconstructed plasma appearance.
Instant – 4.8 ms, total radiation absorption, anode at the top.

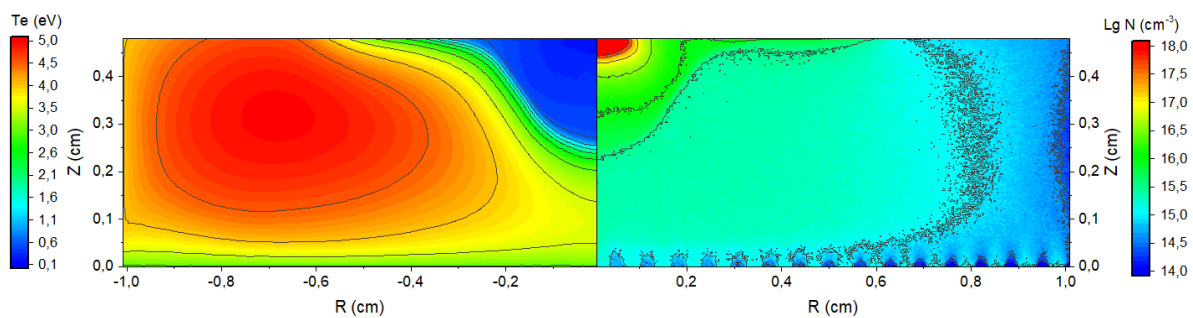


Figure 5. Left side – electron temperature, right side – total plasma density (ions and atoms).
Instant – 4.8 ms, total radiation absorption, anode at the top.

Anode plasma plume looks like a relatively dark blob surrounded by bright shell. The plume looks much brighter than interelectrode plasma (figure 4). The plasma plume temperature is considerably smaller than the interelectrode plasma temperature. The density in plasma plume is much higher than the interelectrode plasma density. In addition, the plasma ionization degree in the plume is much less than unity. Electrical conductivity of the plasma in the plume is low. Thus, the arc current tends to flow around the plume (figure 4). All this leads to the fact that the electron and ion flows to the anode at the base of the plume are negligible. The high temperature there is maintained solely by the flow of radiation energy from the plasma. Thus, the radiation flux from the interelectrode plasma to the anode is the main cause of the appearance of the anode plume.

It is necessary to tell that after the anode plasma plume appearance the assumption that the interelectrode plasma is optically thin may be violated. Radiation can be trapped in the dense plasma plume. This can lead to stopping the growth of the plume or even to its disappearance.

3. Conclusion

A self-consistent simulation of anode heating during the 50 Hz HCVA contact opening was carried out. The calculations were done in the framework of hybrid HCVA model [13, 14]. The occurrence of an anode plasma plume (similar to that found in experiments [6–8]) was obtained as a result of modeling. It is shown that one of the main reasons for the appearance of the anode plume is the flux of line radiation energy from the interelectrode plasma to the anode.

Acknowledgments

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